Final Report

CCEM Key Comparison CCEM. M.-K1

“ Magnetic Flux Density by means of Transfer Standard Coil“

March 2005

Kurt Weyand
Electricity Division
Physikalisch-Technische Bundesanstalt
Bundesallee 100, D-38116 Braunschweig, Germany
e-mail: Kurt.Weyand@ptb.de

Participants

K.Weyand, J.Lüdke, R.Ketzler
Physikalisch Technische Bundesanstalt - PTB, Braunschweig, Germany

P.G.Park
Korea Research Institute of Standards and Science - KRISS, Taejon, Republic of Korea

V.Shifrin
D.I.Mendeleyev Institute for Metrology - VNIIM, St. Petersburg, Russian Federation

V.Balakrishnan
National Measurement Laboratory, - NML CSIRO (now National Measurement Institute Australia (NMIA)), Lindfield, Australia

L.Dorosinski
Tübitak Ulusal Metroloji Enstitüsü - UME, Gebze-Kocaeli, Turkey

M.Hall, J.Bartholomew
National Physical Laboratory - NPL, Teddington, United Kingdom

G. Crotti, F. Fiorillo
Istituto Elettrotecnico Nazionale "Galileo Ferraris" -IEN,Torino, Italy

Z.Wei
National Institute of Metrology - NIM, Beijing, China

J. Kupec
Czech Metrology Institute - CMI, Praha, Czech Republic

M.A.Escobar
Centro Nacional de Metrologia - CENAM, Queretaro, Mexico

Comparison support group: M. Hall, NPL, UK (coordinator)
G. Crotti, IEN, IT
K. Weyand, PTB, DE

Introduction

The delegates of the CCEM discussion meeting on international comparisons in magnetism - 15th of May 2000 in Sydney - recommended that a world-wide comparison of the magnetic flux density by means of a transfer standard coil should be proposed in addition to and in accordance with the EUROMET Project No. 446, which had been finished in March 2000. This comparison did not follow the formal rules of a key comparison. At the meeting of the CCEM Working Group on Low Frequency Quantities (WGLF, ex Working Group on Key Comparisons (WGKC)) in Paris, on 13 September 2000, it was decided that an international CIPM Key Comparison of B/I according to Doc. WGKC Sep00-9 should be prepared with the Physikalisch-Technische Bundesanstalt (PTB) as the pilot laboratory. The document mentioned was circulated to the CCEM members as a "call for participation" in November 2000.

The transfer standard

A single layer solenoid of the Garret type [1],[2] with a winding length of about 350 mm and a diameter of 122 mm was prepared by PTB to serve as dc- and ac-transfer standard. The coil former is made of ceramics, the winding of the solenoid is fixed by means of epoxy. The standard is capable of carrying a maximum permitted current I_C of 1 A, producing a field in its centre with a flux density B_0 of about 2 mT. The field in the centre region is as homogeneous as necessary to enable NMR measurements - protons in H_2O - by the free precession method even for fields larger than 1 mT. Four diametrically arranged current return leads along the coil, fixed at the same distance from the coil axis and resistively equalised, ensure general compensation of field components perpendicular to the coil axis and reproducible connection conditions for all participants. Figure 1 shows the field profile on the coil axis related to the centre field of about 1 mT, whereby the flux density was measured using a fluxgate magnetometer with 5 mm sensor length and the position by means of an optical length measuring system. In addition, VNIIM checked the homogeneity applying ac currents with frequencies up to 20 kHz. The deviation at $\Delta x = \pm$ 20 mm from the centre value was over the whole frequency range less than 0.05 %, whereby the relative uncertainty of these measurements was also estimated to be 0.05 %.

At the one end of the coil a Pt 100 resistor R_T is fixed to the winding provided as a coil temperature reference. By varying the room temperature, the temperature coefficient of the coil constant $k_{dc} = B_0/I_C$ with respect to the change of R_T was measured applying NMR according to figure 2. From the slope the temperature dependence follows as

$$\frac{k_{dc}(R_T)}{k_{dc}(R_{T0} = 109.1\Omega)} - 1 = -(17.0 \pm 1) \cdot 10^{-6} \left\{ \frac{R_T}{\Omega} - 109.1 \right\}, \qquad (1)$$

with R_{T0} corresponding to 23 °C.

VNIIM gave a hint that, besides the correction according to equ. (1), the coil constant depends on current I_C. This was later investigated in PTB applying NMR at different currents with the result presented by figure 3. The reported values have therefore been corrected according to

$$\frac{k_{dc}(I_C)}{k_{dc}(I_C=0)} - 1 = -(84.0 \pm 2) \cdot 10^{-6} \cdot \left(\frac{I_C}{\mathrm{A}}\right)^2 , \qquad (2)$$

as far as the measurements were carried out with currents larger than 0.1 A.

During circulation, the standard coil was damaged two times; the first time on the way from UME to NPL and the second time on the way from CMI via PTB - for customs clearance - to CENAM. In the first case the coil body had to be repositioned in the end flanges, in the second case the equalising resistor network had partly to be replaced and the current leads had to be fixed again.

Measurements with dc currents

Table 1 presents the methods by which the unit of flux density is maintained at the various laboratories as well as the method by which the transfer standard was related to the particular standard. Three laboratories - KRISS, VNIIM and NIM - applied Atomic Magnetic Resonance, three other laboratories - NPL, CENAM and PTB - Nuclear Magnetic Resonance. At CENAM a commercially fabricated flowing water instrument was used, while NPL and PTB applied free precession using a pure H_2O sample. All results are based on the newest γ_P value recommended by CODATA in 1999. NPL also reported a value measured by applying ESR. Three other laboratories – NML CSIRO, UME and IEN - used Hall sensors to relate the field of the transfer standard to that of their own field standard which are also partly based on NMR. CMI superposed the field of an additional Garret coil which fits into both the transfer standard and its own standard coil, to compensate the field of the particular coil under test using a flux gate magnetometer, providing a resolution of 1 nT for zero reading. The relation of the constants of the coils to be compared is then in accordance with the ratio of currents.

Table 1 Measuring methods and conditions

Institute	Field standard of the institute	Transfer measurements by means of	DC current through Transfer Standard A	R_T Ω
KRISS	AMR ^4He	AMR ^4He	0.1 to 0.3	108.7 to 109.1
VNIIM	AMR He-Cs	AMR ^4He	0.2 to 0.3	109.3 to 109.8_5
NML CSIRO	Reference coil, NMR based	Hall-Magnetometer	0.23 to 0.96	109.6 to 110.3_5
UME	Hall-Magnetometer	Hall-Magnetometer	0.9	109.0
NPL	NMR	NMR	0.01 to 0.04	108.2
	ESR	ESR	0.59 to 0.75	109.0
IEN	Reference coil, NMR based	Hall Magnetometer	0.42	108.3 to 109.1
NIM	NMR	AMR ^4He	0.025 to 0.05	107.3 to 107.8_5
CMI	Garret coil, NMR based	Field superposition, flux gate magnetometer	0.2 to 0.35	109.4 to 109.6
CENAM	NMR, flowing water	NMR, flowing water	0.5 to 0.6	109.9_5 to 110.2
PTB	NMR	NMR	0.2 to 0.6	108.3 to 112.3

The fourth column states the dc currents applied to the transfer coil to perform the measurements and in the last column the resistance of the Pt100 resistor R_T observed during the measurements is given. All participants reported the value of the coil constant with respect to R_T = 109.1 Ω.

Table 2 presents the coil constant values as reported; the number of series of measurements; the values calculated from the reported values by correcting for currents larger than 0.1 A using equation (2), and the 1σ-uncertainties as quoted by the various institutes.

The both values reported by NPL differ by about $150 \cdot 10^{-6}$. Since the ESR measurement was carried out with currents about 20 times larger than applied for the NMR measurements, following equ. (2) the ESR value should be about $35 \cdot 10^{-6}$ lower than the NMR value. For that reason the ESR value is believed to be erroneous and only the NMR value is further taken into account.

The value of CENAM, marked by (*), is the reported one, but corrected for the Earth's field component perpendicular to the standard coil field. Nevertheless, the value is still more than 0.1 % above all the other AMR or NMR values. Tests carried out with the flowing water instrument of CENAM in March 2003 at PTB led to the supposition that the somewhat sophisticated method of interpolating the absorption line centre frequency was probably applied in a wrong way.

For that reason the CENAM value as well as all reported values having 1σ-uncertainties larger than 10^{-4} were not used to estimate the mean value of the coil constant of the standard.

PTB performed the measurement three times: before, during and after circulating the transfer standard to determine whether the coil values had changed during transport. The listed value is the mean of 33 measuring runs during the three periods, while the listed uncertainty is that of a single run.

Table 2 Results of dc coil constant determination

Institute	$k_{dc,I,rv}$ reported value for R_T = 109.1 Ω mT/A	Series of measure-ments N_I	$k_{dc,I}$ corrected for current dependence mT/A	reported rel. standard uncertainty $u_{k,I}$ (k=1) $\cdot 10^{-6}$	weighting factor $WF_I = \frac{1/u_{k,I}}{\sum_I 1/u_{k,I}}$	$k_{dc,I} - k_{wm}$ nT/A	rd_I $(k_{dc,I} / k_{wm}) - 1$ $\cdot 10^{-6}$
KRISS	2.024 105	12	2.024 113	4	0.148	- 15.7	- 7.8
VNIIM	$2.024\ 116_5$	6	$2.024\ 130_4$	1.1	0.539	1.6_5	0.8_2
NML CSIRO	2.024 73	18	2.024 87	430	----	739	365
UME	2.055 0	1	2.055 1	278	----	31 000	15 000
NPL, NMR	2.024 19	27	n.c. 2.024 19	73	0.008_3	61.3	30.3
NPL, ESR	2.024 49	15	2.024 56	64	----	430	212
IEN	2.023 53	4	2.023 56	222	----	- 569	- 281
NIM	2.024 108	10	n.c. 2.024 108	8.6	0.069	- 20.7	- 10.2
CMI	2.024 195	3	2.024 206	35	0.017	77.3	38.2
CENAM	2.026 43*	3	2.026 48	62	----	2351	1162
PTB	-	33	$2{,}024\ 133_6$	2.7	0.22	4.8_5	2.4
$CENAM_{PTB}$	2.024 158	2	2.024 201	32	----	72	35.5

Since the uncertainties of the six remaining values still differ by nearly two orders of magnitude, the reciprocal of the individual uncertainty was defined as the weighting factor in order to determine a weighted mean value k_{wm} of the standard according to

$$\boldsymbol{k_{wm}} = \sum_{\mathbf{I}} \boldsymbol{k}_{\mathbf{dc,I}} \cdot \mathbf{WF_I} \qquad \text{with}$$

$$\mathbf{WF_I} = \frac{1/\mathbf{u_{k,I}}}{\sum_{\mathbf{I}} 1/\mathbf{u_{k,I}}} \quad \text{and} \qquad \sum_{\mathbf{I}} \mathbf{WF_I} = \mathbf{1}\,.$$

The third-last column in table 2 presents the weighting factors; the last two columns show the deviation of the laboratory values from the weighted mean value k_{wm}.

The uncertainty of k_{wm} over the two years of circulation has been determined from three terms:

a) the individual deviations from the weighted mean rd_I combined with the reported individual uncertainty $u_{k,I}$ and weighted in the same way as the individual coil constant values :

$$\mathbf{u_I} = \sqrt{\sum_{\mathbf{I}} (\mathbf{rd_I^2} + \mathbf{u_{k,I}^2}) \cdot \mathbf{WF_I^2}} = \mathbf{2.21 \cdot 10^{-6}}\,,$$

b) the uncertainty of the correction for different currents:

$$\mathbf{u_C} = \mathbf{2 \cdot 10^{-6}}\,,$$

c) the possibility of a change of k_{wm} over time due to a damage; this has been estimated from the weighted mean values of the three measurements in 2001 - $k_{wm,2001}$ - and the four measurements in 2002 - $k_{wm,2002}$ -

$$\mathbf{u_V} = \frac{\sqrt{(\boldsymbol{k}_{\mathbf{wm,2001}} - \boldsymbol{k}_{\mathbf{wm}})^2 + (\boldsymbol{k}_{\mathbf{wm,2002}} - \boldsymbol{k}_{\mathbf{wm}})^2}}{\boldsymbol{k}_{\mathbf{wm}}} = \mathbf{4.91 \cdot 10^{-6}}\,.$$

The combined relative standard uncertainty of the coil constant amounts to

$$\mathbf{u(\boldsymbol{k}_{wm})} = \sqrt{\mathbf{u_I^2} + \mathbf{u_C^2} + \mathbf{u_V^2}} = \mathbf{5.7_5 \cdot 10^{-6}}$$

The final result with the standard deviation expanded by k = 2 is

$$\boldsymbol{k}_{\mathbf{wm}} = \mathbf{(2.\ 024\ 129 \pm 0.\ 000\ 023_3)\ mT/A = 2,\ 024\ 129 \cdot (1 \pm 11.5 \cdot 10^{-6})\ mT/A}\,.$$

The diagram of figure 4 shows the relative deviation of the coil constant determination by the various institutes and the measurement period. Eight of ten participants agree within their 2σ-uncertainties with the weighted mean within its 2σ-uncertainty. Due to the fairly large uncertainty of the KCRV (11.5 ppm) with respect to the expanded uncertainty of some of the participants (2.2 ppm and 5.4 ppm respectively), the uncertainty of the KCRV was not included in the uncertainty of the DoEs.

Measurements with ac currents

Eight institutes have also measured the frequency dependence of the coil constant and have reported their results as $k(f)/k_{dc}$ values again with respect to R_T = 109.1 Ω. Besides UME - they used the same Hall-magnetometer up to f = 200 Hz as for the dc measurements - all laboratories applied search coils, but in quite different ways.
KRISS, VNIIM, NPL and IEN used search coils which had previously been calibrated in a standard coil of their own. They all measured the current as the voltage drop across an ac-shunt resistor and the induced voltage by two DVMs of the same type. NPL used this technique from 60 Hz to 15 kHz. Additionally, NPL calculated the coil constant from the effective area of the search coil and the mutual inductance of the transfer and search coil measured at a frequency of f = 20 Hz.
NIM also used a calibrated search coil, but the voltage drop across the shunt resistor and the induced voltage were measured alternately by means of an lock-in amplifier.
CMI used two search coils with nominally the same sensitivity factor of 1,3 Wb/T. One search coil was placed in the transfer coil, and the other in the CMI standard coil, the frequency dependence of which is well known. Both the field coils were positioned at a distance of three meters apart and they were connected in series, so that they were carrying the same current during the measurements. The voltages induced in both search coils were compared by means of inductive voltage dividers and a selective nanovoltmeter. This procedure was repeated after transposing the search coils to eliminate their coil factors from the result.
The PTB recorded the mutual inductance of the search coil inside the field coil by measuring the current through the field coil and the voltage induced in the search coil as a function of frequency using the same instrument. Where the mutual inductance does not change with increasing frequency, the value of the coil constant for dc is still valid. It is always possible to extrapolate to the dc-value by polynomial fitting. This philosophy differs a little from that using a calibrated search coil. Although this method needs more measuring points at various frequencies, it is of some advantage: there is no need to place the sensor exactly in the centre of the field coil nor to align it to its axis, moreover, if the same instrument is used for current and voltage measurement, its frequency response does not affect the measurement provided this does not depend on the voltage level. PTB applied different search coils, the frequency response of which had been linearized by means of a resistive network with respect to the DVM input impedance and with respect to the connection cable.
Table 3 shows the frequency ranges covered by the various institutes as well as the 1σ-uncertainties reported by them.

Again, PTB performed the measurements two times to establish any change in the transfer standard. As can be seen in figure 5, within the stated expanded uncertainty (k=2) there is no detectable change over the period in which the coil was circulated.

Table 3 Frequency ranges and reported uncertainties of the ac measurements

Institute	Frequency f kHz	reported uncertainty $u_{Q(f),I}$ (1σ) $\cdot 10^{-2}$	Frequency f kHz	reported uncertainty $u_{Q(f),I}$ (1σ) $\cdot 10^{-2}$	Frequency f kHz	reported uncertainty $u_{Q(f),I}$ (1σ) $\cdot 10^{-2}$
KRISS	0.1 to 1	0.08	1.1 to 5	0.13	5.1 to 20	0.22
VNIIM	0.06 to 6.3	0.07	10 to 20	0.17		
UME	0.05 to 0.2	0.4				
NPL	0.02	0.039	0.06 to 20	0.2		
IEN	0.02 to 6	0.16	8 to 10	0.17	12 to 20	0.18 to 0.28
NIM	0.03 to 20	0.22				
CMI	0.04 to 0.88	0.03	1.22 to 4.8	0.059	7.2 to 20	0.24
PTB	0.02 to .99	0.04	1 to 9.9	0.08	10 to 20	0.17

Due to the current distributing networks on both flanges of the standard coil, each including a short-circuiting loop, the frequency dependence differs from the usually observed one; the function $Q(f) = k(f)/k_{dc}$ shows a minimum at about 4 kHz. This was designed in order to provide a frequency dependence differing from that of the standard coil used in the EUROMET project. As shown by figure 6, six of the eight institutes, which performed ac-measurements, have in general fulfilled this function, one measured a quite different function and one failed even at low frequencies - at f = 200Hz the value of UME deviates by more than 3 %.

For this reason, the values presented by UME and NIM have not been used to calculate the fit curve $P(f) = ((k(f)/k_{dc})_I)_{fit}$ by means of partial polynomial least squares adjustment of all values $(k(f)/k_{dc})_I$ presented by the six remaining institutes.

The individual uncertainties of the ac measurements do not differ in the manner of the measurements using dc, therefore a weighting procedure has not been applied. Figure 7 presents the relative combined uncertainty $u_{ac}(f)$ of the curve $P(f)$ as evaluated by polynomial fitting of the relative uncertainty of all individual measured values $Q_I(f)$ according to

$$\mathbf{u}_{\mathbf{ac,I}} = \sqrt{[\mathbf{Q}_\mathbf{I}(f) - \mathbf{P}(f)]^2 + \mathbf{u}^2_{\mathbf{Q(f),I}}} \ .$$

The standard uncertainty of $P(f)$ increases from 0.08 % at low frequencies to about 0.33 % at f = 20 kHz, whereby the individual $u_{ac,I}$ points above the fit line dominate the final uncertainty of $P(f)$ at the particular frequency.

As shown by figure 6, all values reported by the six institutes agree with $P(f)$ within the expanded uncertainty (k = 2).

Final remarks

The results presented in this first world-wide international comparison offer a good view of the capabilities of the participants to disseminate the magnetic quantity "flux density" as maintained using an artefact as a transfer standard. They agree well with the results obtained within the EUROMET Project No. 446 [3]. Compared with this, the uncertainty of the dc measurements could be reduced by more than a factor of 2, the uncertainty of the ac measurements is almost the same. A large contribution to the uncertainty had to be assigned because of possible damages of the standard during transportation.

With respect to the measurements of the coil constant at dc, eight of ten participants' results agree with the weighted mean within a 2σ uncertainty. The reason for the deviation of another one could be cleared up after finishing the comparison, thus they will also agree in future. Four of the participants show particularly good agreement within 10^{-5}. Besides, the dc measurements confirm the supposition that NMR- and AMR-methods should be regarded as the most accurate, followed by the ESR-technique which again proves to be more accurate than the measurements applying Hall-elements.

With respect to the measurements of the frequency dependence of the coil constant, six of eight participants' results agree well up to a frequency of 20 kHz, though an unusual dependence on frequency has been established. One participant did not meet the curve progression within 2σ and one failed it remarkably even at low frequencies.

The overall good agreements of this comparison are particularly notable, as there are a number of different measurement techniques being used. In case of a further intercomparison in future, a modified transfer standard having a very low temperature coefficient based on recent developments could be provided and a more reliable way of transportation must be found.

References

[1] M.W.Garrett: "Axially Symmetric Systems for Generating and Measuring Magnetic Fields", J.Appl.Phys., vol. 22, pp 1091-1107, 1951.

[2] M.W.Garrett and S.Pissanetzky: "Polygonal Coil Systems for Magnetic Fields with Homogeneity of the Fourth to the Eigth Order", Rev. of Sci. Instr., vol.42, pp 840-857, 1971.

[3] K.Weyand et al.: "Final Report on EUROMET Project No. 446", Metrologia, 38, pp 187-191, 2001

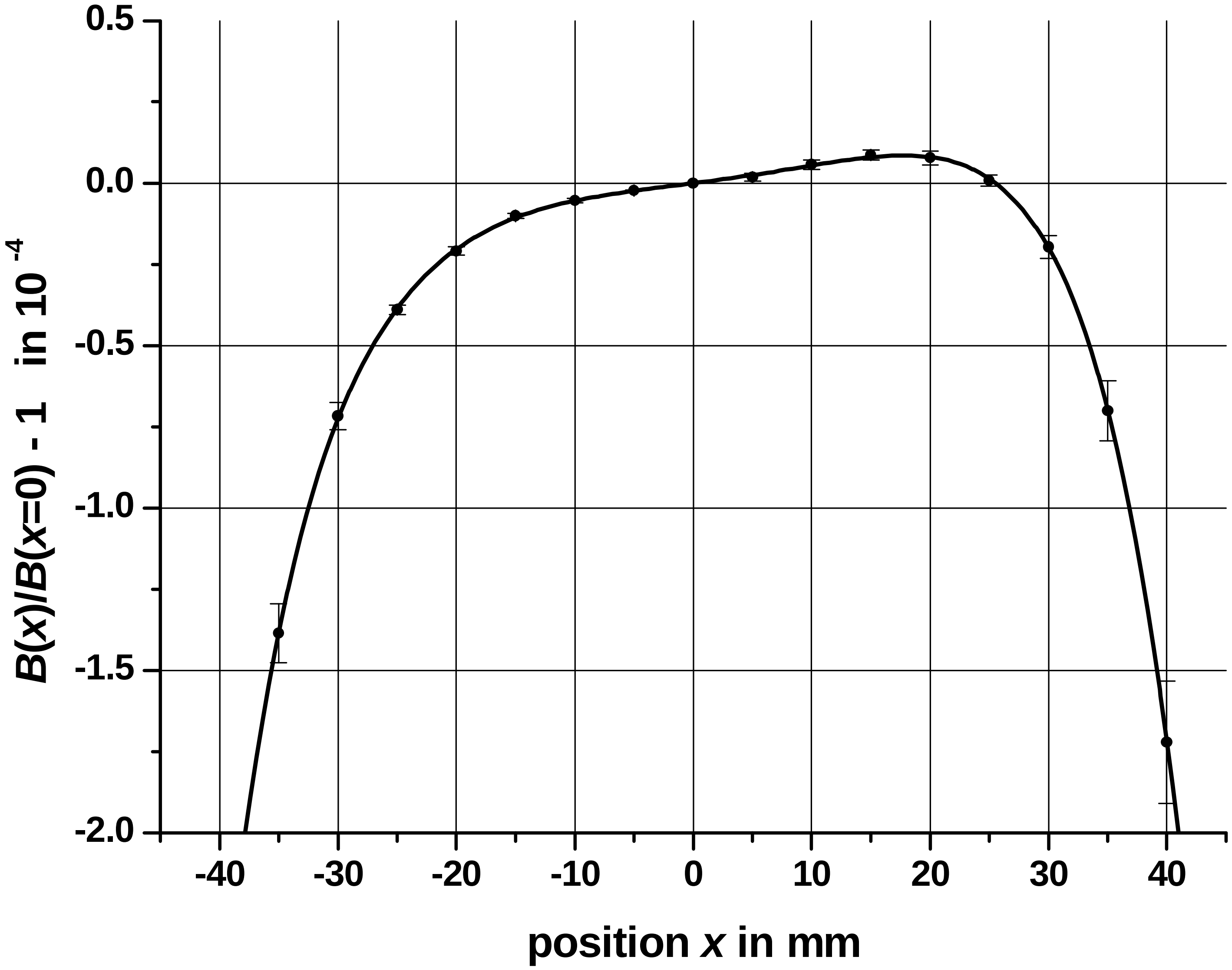

Fig. 1 **Field profile of the transfer standard. The measured values are fitted by a fourth-order polynomial.**

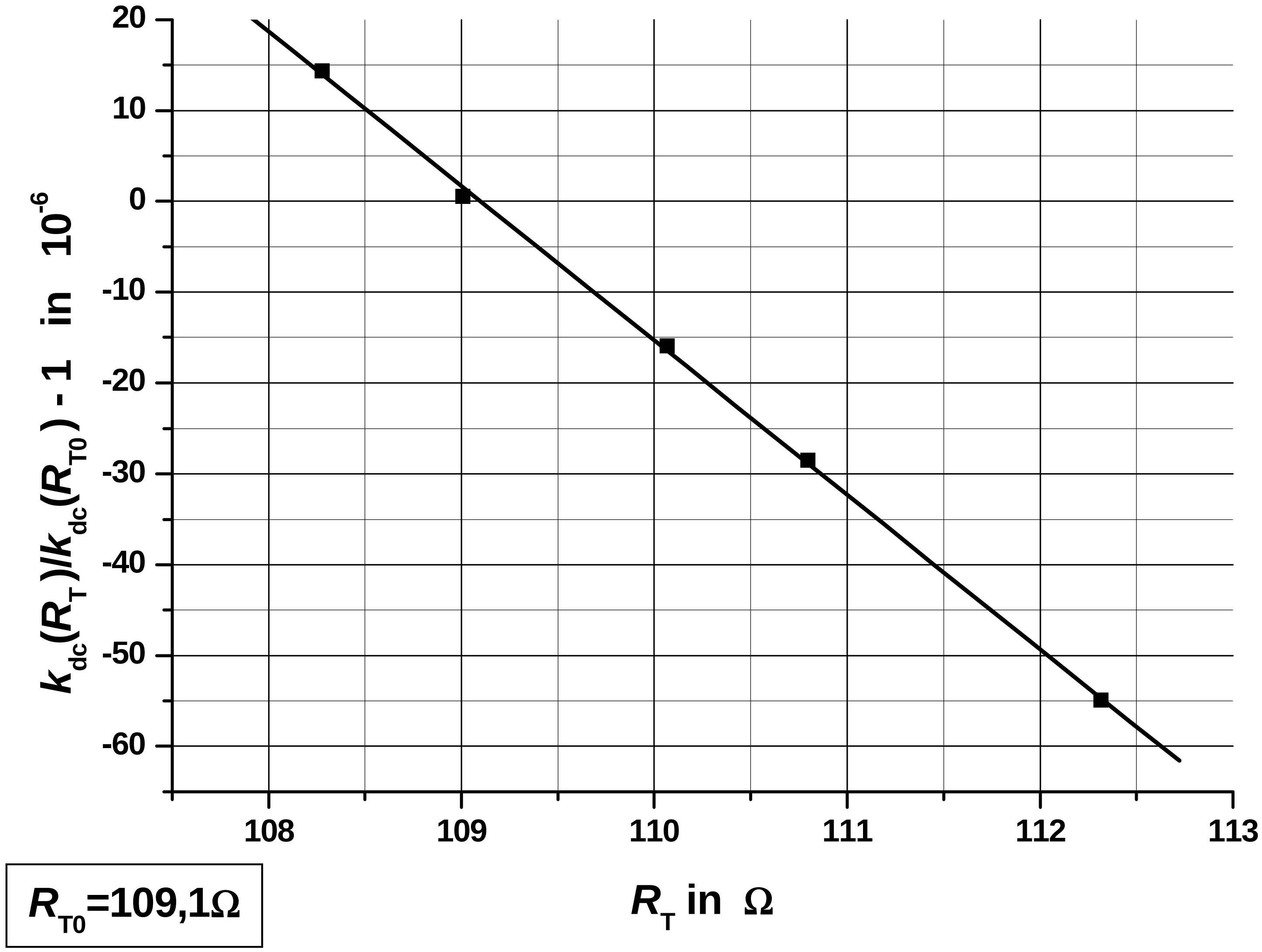

Fig. 2 **Change of k_{dc} as function of the PT 100 resistance R_T fixed to the coil.**

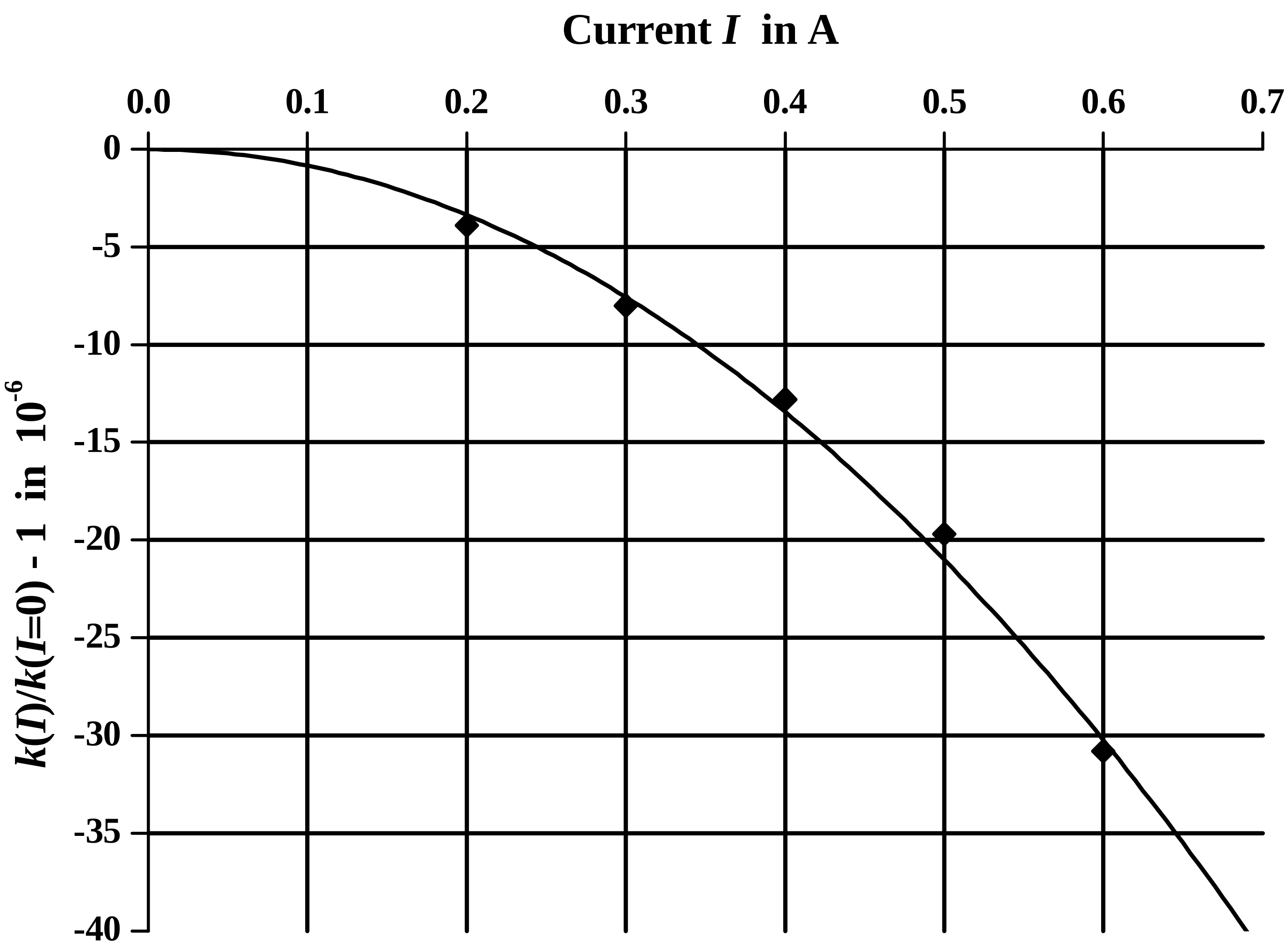

Fig. 3 **Change of k_{dc} as function of current I_C through the coil, when the correction for R_T has been applied.**

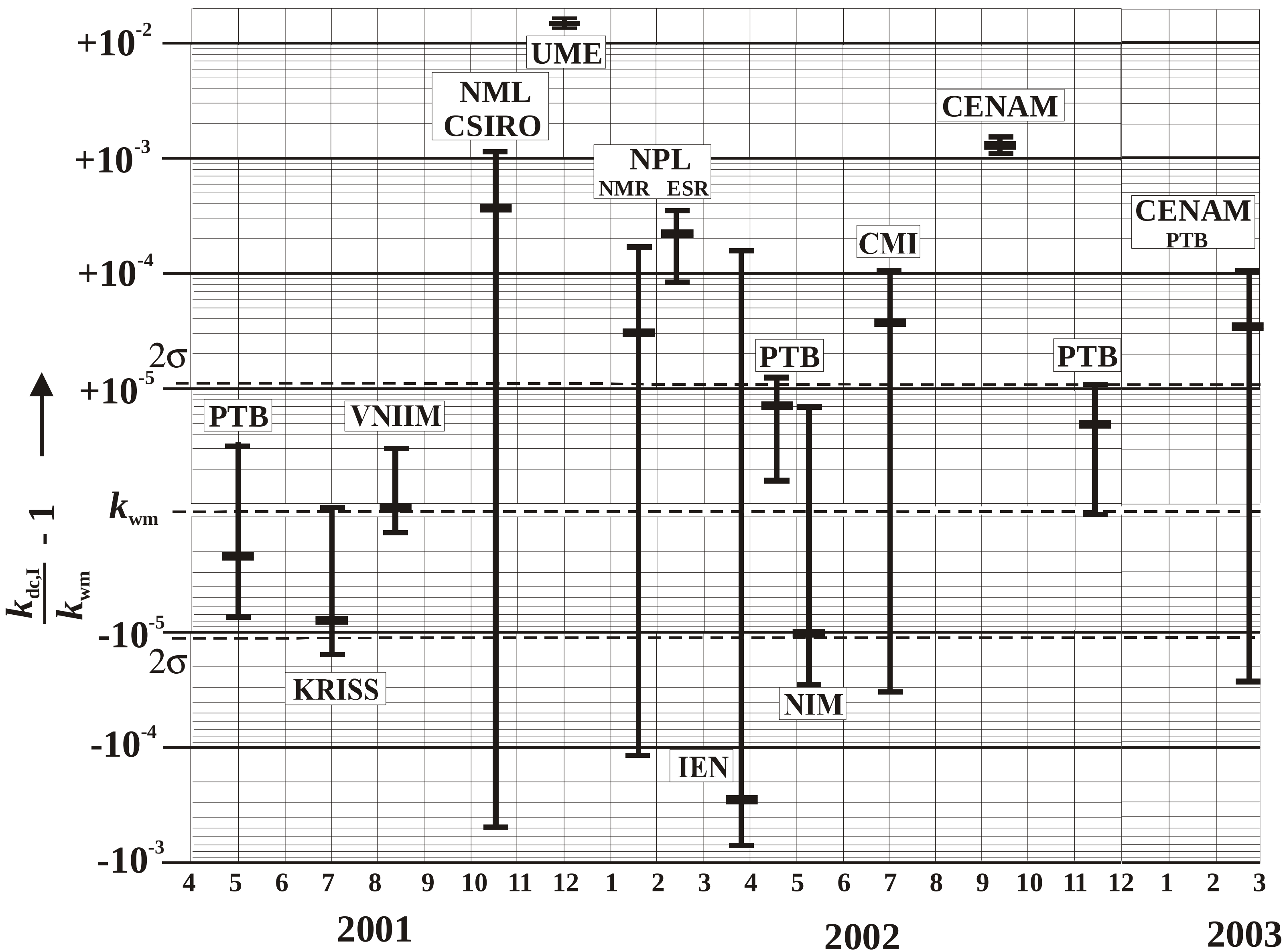

Fig. 4 Dc coil constant determination by the various institutes plotted against the period when the measurements were carried out. The 2 σ lines represent the uncertainty of the weighted mean value k_{wm}.

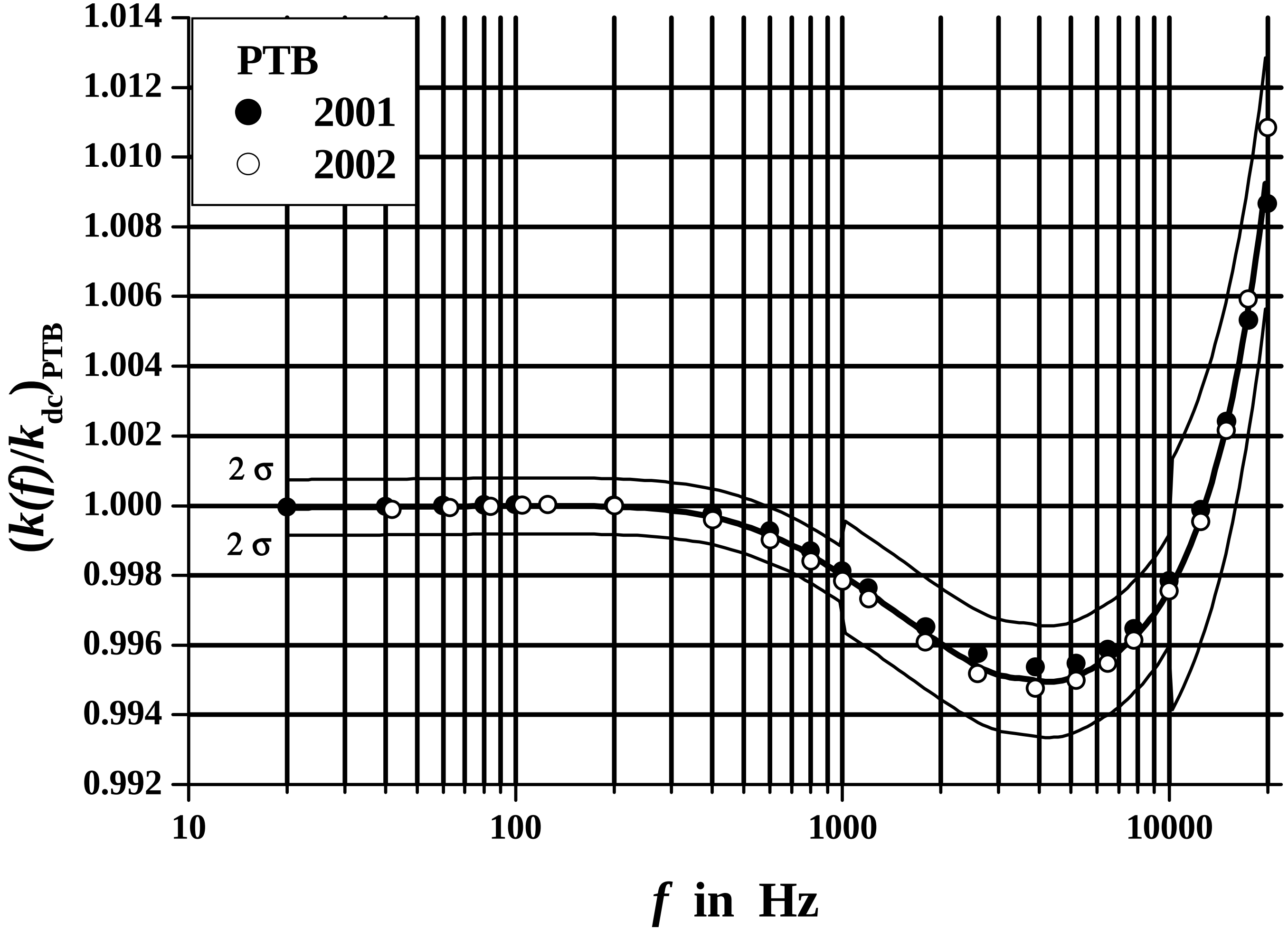

Fig. 5 **Frequency response of the transfer standard as measured at the PTB before and after circulating the standard. The 2 σ lines are according to the uncertainty values presented in table 3.**

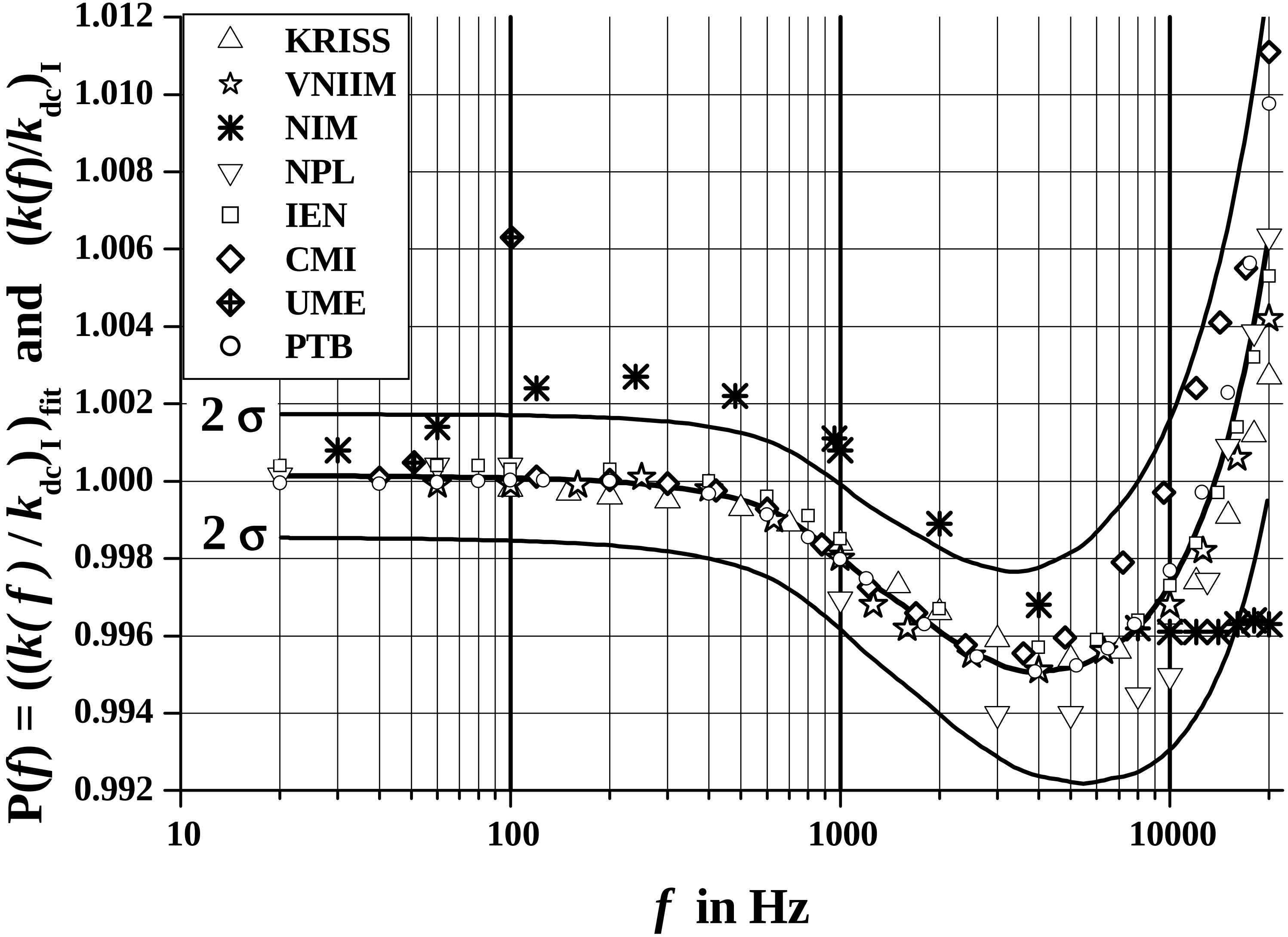

Fig. 6 **Frequency dependence of the coil constant as measured by all institutes, the 2 σ lines are according to the uncertainty function presented in fig. 7.**

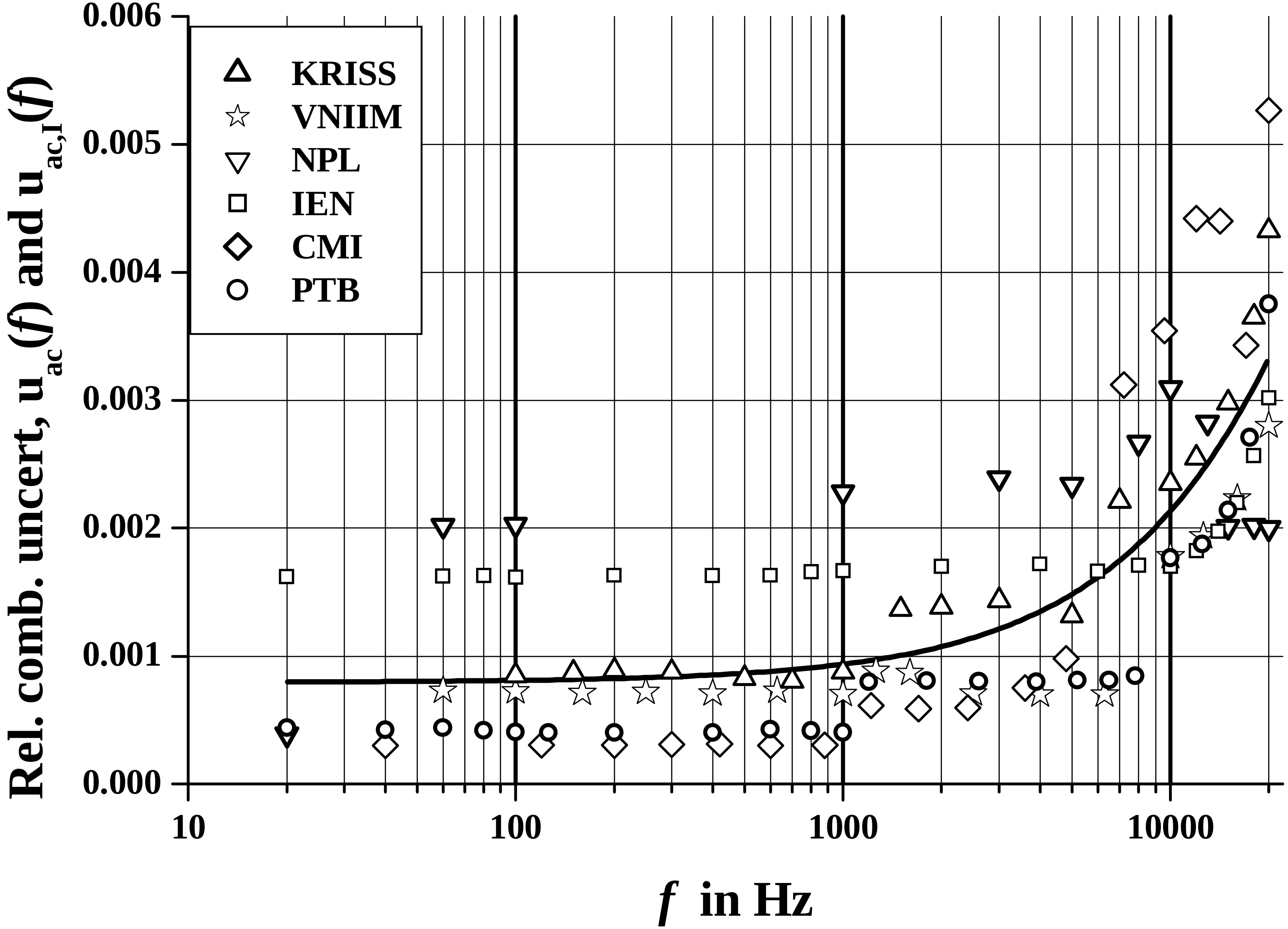

Fig. 7 **Uncertainty of the fit curve P(*f*) evaluated from the individual $k(f)/k_{dc}$ values reported by the institutes as cited.**

CCEM.M.-K1

Appendix 1

Individual uncertainty budgets

KRISS uncertainty budget for reported k_{dc}

Source of Uncertainty	Type	*Relative Standard* Uncertainty in 10^{-6}
Scattering of observations, random	A	2.8
Helium-4 AMR determination	B	0.6
Transfer standard field non-uniformity	B	2.0
Current source instability	B	2.0
Standard uncertainty of the low field standard system (KRISS)	B	0.3
RSS of Type A uncertainties		**2.8**
RSS of Type B uncertainties		**2.9**
Combined uncertainty (1 σ)		**4.0**
Reported uncertainty		**4.0**
Expanded reported uncertainty (k=2)		**8.0**

KRISS uncertainty budget for $k(f)/k_{dc}$

Measuring frequency: ***range 1: 100 Hz to 1 kHz***
range 2: 1.1 kHz to 5 kHz
range 3: 5.1 kHz to 20 kHz

Source of Uncertainty	Type	Relative Standard Uncertainty in %		
		range 1	*range 2*	*range 3*
Scattering of observations	A	0.01	0.014	0.032
Calibration of search coil	B	0.05		
Coil position and angle	B	0.0115		
DVM1 (current)	B	0.0289	0.05	
DVM2 (signal)	B	0.0289	0.05	
Standard resistor	B	< 0.0006	< 0.001	
Frequency counter	B	< 0.0006	< 0.001	
Parasitic field	B	0.0115	0.02	
Noise	B	0.0115	0.02	
Environment	B	0.0115	0.02	
DVM2 frequency-response	B	0.0346	0.06	
Coil frequency-response	B			0.0115
DVM1 frequency-response	B			0.0173
Cable capacitance bypassing resistor	B			0.0115
Solenoid-to-coil-capacitance	B			0.1732
Two-coils difference in 0.1 to 1 kHz	B		0.052	
k_{dc} uncertainty (σ_{dc})	B	< 0.001		
RSS of type A uncertainties		**0.01**	**0.014**	**0.032**
RSS of type B uncertainties		**0.077**	**0.123**	**0.214**
Combined uncertainty		**0.078**	**0.124**	**0.216**
Reported uncertainty		**0.08**	**0.13**	**0.22**
Expanded reported uncertainty (k=2)		**0.16**	**0.26**	**0.44**

VNIIM uncertainty budget for reported k_{dc}

Source of Uncertainty	Type	*Relative Standard* Uncertainty in 10^{-6}
Scattering of observations, random	A	0.2
Helium-4 gyromagnetic	B	0.18
Conversion coefficient of the QCM	B	0.3
Helium-4 AMR frequency	B	0.1
Temperature	B	0.2
Transfer standard non-uniformity (systematic)	B	1.0
RSS of Type A uncertainties		**0.2**
RSS of Type B uncertainties		**1.08**
Combined uncertainty (1 σ)		**1.1**
Reported uncertainty		**1.1**
Expanded reported uncertainty (k=2)		**2.2**

VNIIM uncertainty budget for $k(f)/k_{dc}$

Measuring frequency: ***range 1: 60 Hz to 9.9 kHz***
range 2: 10 kHz to 20 kHz

Source of Uncertainty	Type	Relative Standard Uncertainty in %	
		range 1	*range 2*
Repetition of measurements	A	0.02	
Calibration of search coil	B	0.03	
Coil position and angle	B	0.01	
DVM1 (current)	B	0.03	
DVM2 (signal)	B	0.03	
Standard resistor	B	0.03	
Environment	B	0.01	
Transfer standard current supplying cable	B		0.15
RSS of type A uncertainties		**0.02**	
RSS of type B uncertainties		**0.062**	**0.162**
Combined uncertainty		**0.065**	**0.163**
Reported uncertainty		**0.07**	**0.17**
Expanded reported uncertainty (k=2)		**0.14**	**0.34**

CSIRO-NML uncertainty budget for reported k_{dc}

Source of Uncertainty	Type	*Relative Standard* Uncertainty in 10^{-6}
Magnetometer reading with NML coil (B_1)	A	31
Magnetometer reading with standard coil (B_2)	A	31
NML Helmholtz coil constant (K_1)	B	72
Temperature effect on K_1	B	335
Non-linearity of Helmholtz coil K_1	B	255
Voltage across R_1	B	3
Shunt with NML coil (R_1)	B	5
Voltage across R_2	B	3
Shunt with standard coil (R_2)	B	4
RSS of Type A uncertainties		**44**
RSS of Type B uncertainties		**427**
Combined uncertainty (1 σ)		**429.5**
Reported uncertainty		**430**
Expanded reported uncertainty (k=2)		**860**

UME uncertainty budget for reported k_{dc}

Source of Uncertainty	Type	*Relative Standard* Uncertainty in 10^{-6}
Scattering of field observations, random	A	243
Coil current	B	114
Probe position	B	2.3
PTR resistor R_T	B	3.5
RSS of Type A uncertainties		**243**
RSS of Type B uncertainties		**114**
Combined uncertainty (1 σ)		**269**
Reported uncertainty		**278**
Expanded reported uncertainty (k=2)		**556**

UME Uncertainty budget for $k(f)/k_{dc}$

Source of Uncertainty	Type	Relative Standard Uncertainty in %		
		51.2 Hz	*101.2 Hz*	*201.2 Hz*
Coil current	A	0.165	0.027	0.03
Probe position	B	0.00006		
Magnetic field	B	0.39	0.4	0.42
PTR resistor R_T	B	0.0002		
RSS of type A uncertainties		**0.165**	**0.027**	**0.03**
RSS of type B uncertainties		**0.39**	**0.4**	**0.42**
Combined uncertainty		**0.42**	**0.4**	**0.42**
Reported uncertainty		**0.42**	**0.39**	**0.42**
Expanded reported uncertainty (k=2)		**0.84**	**0.78**	**0.84**

NPL Uncertainty budget for reported k_{dc} - NMR measurement

Source of Uncertainty	Type	Relative Standard Uncertainty in 10^{-6}
PRT reading stability	A	1.9
Repeatability	A	20
Calibration of proton resonance magnetometer	B	7.5
Resolution of proton resonance magnetometer	B	2.9
Specification of DVM ± 37 ppm of reading	B	18.5
Specification of DVM ± 6 ppm of range at 15 % of range	B	20
Calibration of DMM 5 ppm of reading	B	2.5
Resolution of DMM	B	57.7
Calibration of resistor	B	5
Non uniformity of field	B	17.3
Circuit coupling	B	17.3
Probe displaced from centre of axis	B	15
PRT resistance measurement	B	0.05
PRT calibration uncertainty	B	0.5
RSS of Type A uncertainties		**20.1**
RSS of Type B uncertainties		**70.65**
Combined uncertainty (1σ)		**73.5**
Reported uncertainty		**73.5**
Expanded Reported uncertainty (k=2)		**147**

NPL Uncertainty budget for $k(\mathrm{f})/k_{dc}$ - frequency range: 60 Hz to 20 kHz

Source of Uncertainty	Type	Relative Standard Uncertainty in %
PRT reading stability	A	0.00019
Repeatability	A	0.02
Calibration of search coil M134	B	0.08
History of search coil M134	B	0.02
Frequency response of search coil M134	B	0.1
Specification of DVM measuring across shunt, ± 0.035 % of reading	B	0.0175
DVM specification, ± 0.015 % of range, at 15 % of range	B	0.05
Calibration of DVM worst case - current	B	0.0375
Value of current shunt	B	0.0005
Frequency response of current shunt	B	0.015
Drift of current shunt	B	0.0866
Specification of DVM measuring coil output, ± 0.035 % of reading	B	0.0175
DVM specification, ± 0.015 % of range, at 12 % of range	B	0.0625
Calibration of DVM worst case – induced voltage	B	0.0375
Loading of DVM on shunt	B	0.0346
Loading of DVM on coil	B	0.0289
Coil not aligned for maximum reading	B	0.02
Coils displaced from centre of axis	B	0.0015
Non uniformity of field	B	0.00173
Circuit coupling	B	0.05774
Uncorrected pickup where RSS of 3.3 mV with 325.3 mV	B	0.003
PRT resistance measurement	B	0.0000048
PRT calibration uncertainty	B	0.00005
RSS of Type A uncertainties		**0.02**
RSS of Type B uncertainties		**0.2**
Combined uncertainty (1σ)		**0.2013**
Reported uncertainty		**0.205**
Expanded reported uncertainty (k=2)		**0.41**

IEN Uncertainty budget for k_{dc}

Source of Uncertainty	Type	Relative Standard Uncertainty in 10^{-6}
Voltage across reference resistor over Hall magnetom. reading - IEN coil	A	21.7
Hall magnetom. reading over voltage across ref. resistor - Trans.Stand.	A	20.8
Helmholtz coil IEN	B	40
Voltmeter calibration for IEN coil	B	12
Correction of temperature for Hall sensor – IEN coil	B	118.6
Zeroing correction for the Hall probe – IEN coil	B	69.2
Earth field contribution – IEN coil	B	16.8
Hall sensor alignment – IEN coil	B	59.3
Voltmeter calibration for transfer standard	B	9.4
Correction of temperature for Hall sensor – transfer standard	B	118.6
Zeroing correction for the Hall probe – transfer standard	B	69.2
Earth field contribution – transfer standard	B	16.8
Hall sensor alignment – transfer standard	B	59.3
Standard coil temperature coefficient	B	0.2
RSS of Type A uncertainties		**30**
RSS of Type B uncertainties		**217**
Combined uncertainty		**219**
Reported uncertainty		**222**
Expanded reported uncertainty (k=2)		**444**

IEN Uncertainty budget for $k(f)/k_{dc}$

budget at two exemplary frequencies: f_1 = 60 Hz and f_2 = 10 kHz, relative uncertainty increases to 0.28 % at f = 20 kHz

Source of Uncertainty	**Type**	**Relative Standard Uncertainty in %**	
		f_1	**f_2**
Coil constant of transfer standard	B	0.024	0.024
Search coil constant	B	0.15	0.15
Voltage ratio of induced voltage and voltage across shunt	B	0.04	0.04
Calibration of voltmeter, search coil	B	0.0094	0.0094
Voltage correction factor depending on frequency, search coil	B	0.0000017	0.049
Calibration of voltmeter, voltage across shunt	B	0.0062	0.0053
Modulus of shunt impedance	B	0.026	0.032
Frequency	B	0.0058	0.0058
RSS of Type B uncertainties		**0.158**	**0.168**
Combined uncertainty (1σ)		**0.158**	**0.168**
Reported uncertainty		**0.16**	**0.17**
Expanded reported uncertainty (k=2)		**0.32**	**0.34**

CMI Uncertainty budget for reported k_{dc}

Source of Uncertainty	Type	Relative Standard Uncertainty in 10^{-6}
Standard deviation of measurement	A	15
Influence of voltage ratio measurement	B	20
Influence of angles of axis of coils	B	20
Influence of changes of resistances during test	B	7
Stability of our transfer coil during test	B	5
Value of CMI standard coil	B	12
Temperature influence	B	4
RSS of type A uncertainties		**15**
RSS of type B uncertainties		**32**
Combined uncertainty		**35**
Reported uncertainty		**35**
Expanded reported uncertainty (k=2)		**70**

CMI Uncertainty budget for $k(f)/k_{dc}$

Measuring frequency: ***range 1: 40 Hz to 1 kHz***

range 2: 1.1 kHz to 5 kHz

range 3: 5.1 kHz to 20 kHz

Source of Uncertainty	Type	Relative Standard Uncertainty in %		
		range 1	*range 2*	*range 3*
Standard deviation of measurement	A	0.021	0.023	0.06
Value of CMI coil standard	B	0.01	0.025	0.075
Influence of frequency char. of CMI standard coil	B	0.01	0.025	0.17
Influence of different angles of axis of meas. coils	B	0.01	0.01	0.01
Influence of measurement of voltage ratio	B	0.012	0.04	0.14
Temperature influences	B	0.005	0.005	0.005
RSS of type A uncertainties		**0.021**	**0.023**	**0.06**
RSS of type B uncertainties		**0.022**	**0.055**	**0.235**
Combined uncertainty		**0.03**	**0.059**	**0.24**
Reported uncertainty		**0.03**	**0.059**	**0.24**
Expanded reported uncertainty (k=2)		**0.06**	**0.12**	**0.48**

NIM Uncertainty budget for k_{dc}

Source of Uncertainty	Type	Relative Standard Uncertainty in 10^{-6}
Earth's field drift during measurement	A	4 to 10
Current through transfer coil	A	0.3 to 1
Voltage across measuring resistor	B	2
Standard resistor	B	0.5
Flux density measured by ^4He magnetometer	B	10 to 20
PT100 resistor	B	0.006
RSS of Type A uncertainties of one measurement series		**4 to 10**
RSS of Type B uncertainties of one measurement series		**10 to 20**
Combined uncertainty (1σ) of ten measurement series		**8.6**
Reported uncertainty		**8.6**
Expanded reported uncertainty (k=2)		**17.2**

NIM Uncertainty budget for $k(f)/k_{dc}$ - frequency range: 30 Hz to 20 kHz

Source of Uncertainty	Type	Relative Standard Uncertainty in %
AC-voltage	B	0.2
Sample resistor	B	0.005
Influence of search coil frequency response and cable capacitance	B	0.1
AC-current through transfer coil	B	0.03
RSS uncertainties		**0.22_5**
Combined uncertainty (1σ)		**0.22_5**
Reported uncertainty		**0.22**
Expanded reported uncertainty (k=2)		**0.44**

CENAM Uncertainty budget for reported k_{dc}

Source of Uncertainty	Type	Relative Standard Uncertainty in 10^{-6}
Centre flux density	A	15
Current through transfer coil	A	15
Pt 100 resistor	A	1
Scattering of observations	A	58
Correction of earth's field component vertical to coil axis	B	10
RSS of Type A uncertainties		**61**
RSS of Type B uncertainties		**10**
Combined uncertainty (1σ)		**62**
Reported uncertainty		**62**
Expanded reported uncertainty (k=2)		**124**

Measurements at PTB applying CENAM flowing water NMR instrument:

Source of Uncertainty	Type	Relative Standard Uncertainty in 10^{-6}
Scattering of frequency observation in one measurement series	A	16.5
Scattering of current observation in one measurement series	A	1.2
Current measuring resistor	B	2
DVM calibration	B	3
Pt 100 resistor	B	1
Correction for dependence on coil current	B	0.7
Determination of centre frequency	B	27
Sample position	B	5
RSS of Type A uncertainties		**16.5**
RSS of Type B uncertainties		**27.7**
Combined uncertainty (1σ)		**32**
Reported uncertainty		**32**
Expanded reported uncertainty (k=2)		**64**

PTB Uncertainty budget for reported k_{dc}

Source of Uncertainty	Type	Relative Standard Uncertainty in 10^{-6}
Scattering of observation	A	1.2
Current measuring resistor	B	1.1
DVM calibration	B	1.7
Difference frequency	B	0.5
NMR sample	B	0.8
Pt 100 resistor	B	0.6
Correction for dependence on coil current	B	0.7
RSS of Type A uncertainties of one measurement series		**1.2**
RSS of Type B uncertainties of one measurement series		**2.4**
Combined uncertainty (1σ) of ten measurement series		**2.7**
Reported uncertainty		**2.7**
Expanded reported uncertainty (k=2)		**5.4**

PTB Uncertainty budget for $k(f)/k_{dc}$

Measuring frequency: ***range 1: 20 Hz to 990 Hz***

range 2: 1 kHz to 9.9 kHz
range 3: 10 kHz to 20 kHz

Source of Uncertainty	Type	Relative Standard Uncertainty in %		
		range 1	*range 2*	*range 3*
Induced voltage	A	0.026	0.012	0.012
Voltage across current measuring resistor R_N	A	0.025	0.012	0.013
Voltage ratio	B	0.009	0.057	0.125
Calibration of R_N	B	0.001	0.001	0.01
Frequency dependence of search coil	B	0.0006	0.023	0.11
Frequency	B	0.0006	0.0006	0.0006
RSS of type A uncertainties		**0.036**	**0.017**	**0.018**
RSS of type B uncertainties		**0.0091**	**0.061**	**0.167**
Combined uncertainty		**0.037**	**0.064**	**0.167**
Reported uncertainty		**0.04**	**0.08**	**0.17**
Expanded reported uncertainty (k=2)		**0.08**	**0.16**	**0.34**

CCEM.M.-K1

Appendix 2

Comparison Protocol

Proposal of an Intercomparison within the CCEM of Magnetic Flux Density by Means of a Transfer Standard Coil.

Preliminary remarks:

The delegates of the CCEM discussion meeting on international comparisons in magnetism - 15th of May 2000 in Sydney - decided that a worldwide intercomparison of the magnetic flux density by means of a transfer standard coil should be proposed in addition to and in accordance with the EUROMET project No. 446 which had been finished in March 2000. At the meeting, NPL (Dr. M. Hall) had agreed to overtake the role of the pilot laboratory, whereas PTB should provide the standard coil. Meanwhile NPL cancelled its agreement for budget reasons and PTB has agreed to pilot the intercomparison. At the time of the meeting in Sydney, at least five Standard Laboratories were interested in participating in this intercomparison:

VNIIM, St.Petersburg, Russia,

NIM, Beijing, China.

KRISS, Taejong, Republic of Korea

ETL, Tsukuba, Japan, (?)

CSIRO-NML, Sydney, Australia,

NIST, Boulder or Gaithersburg, USA.

In the meantime, UME from Turkey has also shown its interest in participation.

In order to find out how the results obtained within the planned intercomparison are in relation with these of the EUROMET project, two of the EUROMET partners, besides PTB, should also participate in the new intercomparison. The NPL has already agreed, IEN, Dr. G. Crotti, has been asked to take part.

Transfer Standard:

A single layer solenoid of the Garret type is prepared to serve as dc- and ac-transfer standard. It provides an inner diameter of about 100 mm and a winding length of 345 mm. The coil has a dc-resistance of 35 Ω and is capable of carrying a maximum permitted current of 1 A, producing a field in its centre with a flux density B_0 of about 2 mT. The field in the centre region is as homogeneous as necessary to enable NMR measurements by the free precession method even for fields larger than 1 mT. Four diametrically arranged current return leads along the coil, fixed at the same distance from the coil axis and resistively symmetrized, ensure general compensation of field components perpendicular to the coil axis and reproducible connection conditions for all participants. The coil is connected by a twisted cable of about 30 cm length with banana plugs at the end. At one end of the coil a PT 100 resistor is fixed to the winding provided as a coil temperature reference. The coefficients for calculating the coil temperature from the resistance measurements, the temperature coefficient of the standard as well as a diagram of the measured flux density profile will be circulated together with the standard.

Program of the intercomparison:

Each participant is asked to determine the dc coil constant k_{dc} - which is the quotient of the centre flux density B_0 over the current I_c through the coil - and to determine its deviation over frequency up to f = 20 kHz. For this purpose the partners shall apply the measuring methods and use the current equipment available to them to maintain and to disseminate the unit of magnetic dc- and ac flux density. All results shall be related to a coil temperature of T_c = 23°C.

With respect to the dc measurements it would be a welcome development if NMR or atomic resonance methods could be applied.

In case of ac measurements, care must be taken that loading the standard capacitively by the measuring circuit should be avoided. Furthermore, the surroundings of the standard during the measurements should be free from metallic materials to avoid loading due to induced eddy currents. (As a rule: no metals within a distance of at least three times the length of the coil.)

Reporting the results

The participating institutes must report their results, i.e. the coil constant k_{dc} and its frequency response $k(f)/k_{dc}$ to the pilot institute as soon as possible, together with uncertainty budgets according to the "Guide to the Expression of Uncertainty in Measurement". It is to expect that the 1σ uncertainty in case of the dc measurement is not larger than 10^{-4}, for measurements with frequencies $f \leq 2$ kHz less than 0.2 % and with frequencies above 2 kHz not more than 0.5 %.

Possible schedule:

If all participants are well prepared to start the measurements just after receiving the standard, a period of three weeks should be enough to perform all measurements including additional checks for reproducibility of the results. Three more weeks have been estimated for transportation of the standard to the next partner. The PTB will arrange all required carnets as far as they can be managed in Germany. Nevertheless, each participant should contact the relevant customs office in advance in order to check, whether special or unusual requirements have to be fulfilled to send the standard to the country of the partner following him. To avoid any delay he should also contact a transportation service company in time.

If all institutes mentioned above finally agree to participate, the standard could be circulated as follows.

Jan. to March 2001: Final tests on standard at PTB and preparation for its transport.

1st of April	VNIIM, Russia	receives standard
15th of May	NIM, China	"
1st of July	KRISS, RoK	"
15th of August	ETL, Japan	"
1st of Oct.	CSIRO-NML, Australia	"

15th of Nov.	NIST, USA	"
1st of January 2002	NPL, UK	"
15th of Febr.	IEN, Italy	"
1st of April	UME, Turkey	"
15th to 31th. of May	Re-measurements at PTB	
1st of Aug.	Final results	

Final remark

Each participating institute will be bound to follow the "Guidelines for CIPM key comparisons" -appendix F to the MRA.